EFFECTS OF SURFACE ROUGHNESS ON ROTATING CYLINDER AND MAGNUS WIND TURBINE IN LOW WIND SPEED CONDITIONS

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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May 2017

Chair : Azmin Shakrine Bin Mohd Rafie, PhD
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In today's world, every functional society depends on electricity. As electricity becomes essential in daily life, demand for sustainable energy increases. However, countries with low wind velocity like Malaysia are unable to use conventional wind turbine for energy extraction. This is due to the absence of high wind velocity required to generate high torque that will rotate the generator of the conventional wind turbine. To extract wind energy from low wind velocity countries, Magnus wind turbine (MWT) that utilizes rotating cylinder was experimentally studied. MWT utilized rotating cylinder blades to harvest wind energy by generating Magnus force perpendicular to the incoming air. Furthermore, a simple surface roughness enhancement will increase the force generated from the rotating cylinder. One of the problems with MWT is that the effect from using enhancement of surface roughness on the rotating cylinder blades on Magnus force and torque generated has not been fully characterized and documented. The studies also included force balance for scaling effect on rotating cylinder size and the smoke flow visualization for visual inspection of boundary layer. Therefore, this research will provide valuable information regarding sanded surface roughness application on MWT through experimental study. The MWT and single rotating cylinder are designed and fabricated based on past researches and patents. All experiments were carried out in a wind tunnel. The proof on concept experiment showed that rotating cylinder produced higher lift force compared to the airfoil under similar condition. Next, force balance experiment demonstrated that as rotating cylinder scale increased, the Magnus force generated also significantly increased. The most significant finding is that the surface roughness enhancement increased the small scale rotating cylinder performance making it to be on par with large scale rotating cylinder. The smoke flow visualization experiment illustrated that by using surface roughness enhancement, the boundary layer separation point is further shifted upstream and since it opposed the incoming wind flow, pressure region and the Magnus force are also increased. Moreover, MWT model was subjected to smooth surface and eight types of surface roughness enhancement on the rotating cylinder blades. The result shows that as frequency of rotation cylinder blades and wind speed increased, depending on surface roughness enhancement used, the torque generated will increase. Furthermore, the result shows that minimum cut-in wind speed

is required to rotate the rotor as the velocity ratio and relative roughness increased. In summary, the outcome shows significant improvement of the effect of sanded surface roughness on the rotating cylinder blades. The sanded surface roughness produces five times higher torque coefficient and rate of change torque in comparison with smooth surface roughness. Hence, scientific community will gain the benefits of the effect on rotating cylinder with sanded surface roughness and will be able to use this data for future research.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KESAN KEKASARAN PADA SILINDER BERPUTAR DAN MAGNUS TURBIN ANGIN DALAM KEADAAN KELAJUAN ANGIN YANG RENDAH

Oleh

OMAR FARUQI BIN MARZUKI

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Dalam dunia hari ini, setiap masyarakat berfungsi dengan bergantung kepada tenaga elektrik. Elektrik menjadi perkara penting dalam kehidupan seharian, permintaan untuk tenaga yang mampan meningkat. Walau bagaimanapun, negara-negara dengan halaju angin yang rendah seperti Malaysia tidak boleh menggunakan turbin angin konvensional untuk mengeluarkan tenaga daripada angin. Ini kerana kelajuan angin yang tinggi diperlukan untuk menghasilkan tork yang tinggi untuk memutarkan penjana turbin angin konvensional. Oleh itu, untuk mendapatkan tenaga daripada halaju angin rendah, turbin angin yang berlainan perlu digunakan iaitu Magnus turbin angin (MWT) yang menggunakan silinder berputar untuk mengeluarkan tenaga daripada angin. MWT menggunakan bilah silinder berputar untuk menuai tenaga angin dengan daya Magnus dijana serenjang dengan udara yang masuk. Tambahan pula, peningkatan kekasaran pada permukaan boleh meningkatkan daya yang dijana dari silinder berputar. Salah satu masalah dengan MWT ialah kesan kekasaran permukaan pada bilah silinder berputar kepada tork dan lif daya yang dijana daripada menggunakan peningkatan tidak dicirikan sepenuhnya dan didokumentasikan. Kajian-kajian itu juga termasuk keseimbangan daya untuk kesan skala pada saiz silinder berputar dan visualisasi aliran asap untuk pemeriksaan visual lapisan sempadan. Oleh itu, kajian ini akan memberikan maklumat yang berharga mengenai kesan kekasaran permukaan kertas pasir pada MWT melalui kajian eksperimen. MWT dan silinder berputar tunggal direka and dibuat berdasarkan kajian lepas dan paten. Semua eksperimen telah dijalankan di dalam terowong angin. Bukti mengenai konsep menunjukkan bahawa silinder berputar menghasilkan daya angkat yang lebih tinggi berbanding dengan aerofoil dalam keadaan yang sama. Seterusnya, alat daya pemberat eksperimen menunjukkan bahawa apabila skala silinder berputar meningkat, daya Magnus yang dijana juga meningkat dengan ketara. Penemuan yang paling ketara ialah peningkatan kekasaran permukaan meningkatkan prestasi silinder berputar kecil setanding dengan silinder berputar berskala besar. Eksperimen visualisasi aliran asap menggambarkan bahawa dengan menggunakan peningkatan kekasaran permukaan, sempadan titik pemisahan lapisan beralih lanjut kehadapan dan menentang aliran angin datang, dengan itu ia meningkat rantau tekanan dan peningkatan daya Magnus. Kemudian MWT model yang dikenakan permukaan licin dan lapan jenis

peningkatan kekasaran permukaan pada bilah silinder berputar menunjukkan bahawa kekerapan bilah silinder putaran dan kelajuan angin meningkat, bergantung kepada tambahan kekasaran permukaan yang digunakan, tork yang dihasilkan akan lebih tinggi. Tambahan pula, kajian ini mendapati kelajuan angin masuk minimum yang diperlukan untuk rotor berputar berkurang kerana nisbah kelajuan dan kekasaran relatif meningkat. Ringkasnya, keputusan menunjukkan peningkatan yang ketara keatas kesan kekasaran permukaan yang dicampur dengan kertas pasir pada bilah silinder berputar. Kekasaran permukaan yang dicampur dengan pasir menghasilkan lima kali lebih tinggi dalam pekali tork dan kadar perubahan tork berbanding dengan kekasaran permukaan licin. Oleh itu, masyarakat saintifik akan mendapat manfaat daripada kesan ke atas silinder berputar dengan kekasaran permukaan yang dicampur dengan pasir dan akan dapat menggunakan data ini untuk penyelidikan masa depan.

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I certify that a Thesis Examination Committee has met on 30 May 2017 to conduct the final examination of Omar Faruqi bin Marzuki on his thesis entitled "Effects of Surface Roughness on Rotating Cylinder and Magnus Wind Turbine in Low Wind Speed Conditions" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

MWT	Magnus Wind Turbine
PIV	Particle Image Velocimetry
HAWTs	Horizontal Axis Wind Turbines
VAWTs FEPA	Vertical Axis Wind Turbines
	Federation of European Producers of Abrasives
TSR	Tip Speed Ratio
LDR	Lift to Drag Ratio
ABS	Acrylonitrile Butadiene Styrene

Symbols

Re	Reynolds number
de/d	Ratio of end plates diameter to cylinder diameter
V	Wind speed velocity
L	Lift force
C_L	Lift coefficient
T	Torque
C_T	Torque coefficient
d	Cylinder diameter
k/d	Ratio of roughness height to cylinder diameter

CHAPTER 1

INTRODUCTION

1.1 Backgrounds

Wind energy is one of the natural resources that naturally replenished and can be used repeatedly. To capitalize this renewable energy, wind turbine is developed for harvesting the wind energy. Furthermore, wind turbine is a green energy and one of the sustainable energy that can fulfil current and future generation's needs (Brundtland, 1987).

Currently conventional wind turbine is dominated by horizontal axis wind turbine used airfoils shape blades for wind harvesting energy in high wind speed conditions. Conventional wind turbine required minimum wind speed of 4 meters per second (m/s) to generate minimal lift and wind speed of 16 m/s to generate optimum lift (Balat, 2009). Thus, an innovative type of wind turbine invention is requiring to harvest wind energy at lower wind speed. There are several types wind turbines that can harvest wind energy at lower wind speed, one of the known type wind turbine is Magnus wind turbine prototypes (Bychkov et al., 2007).

Magnus wind turbine utilizing Magnus force generated from a rotating cylinder. Figure 1.1 shows the Magnus force is perpendicular to the incoming air. Due to Magnus force effect, Magnus wind turbine (MWT) can operate under lowest wind speed condition and preferable under 8 m/s (Bychkov et al., 2007).

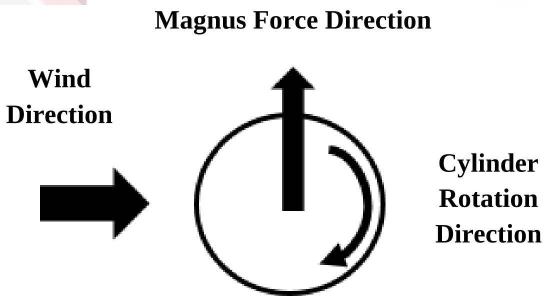

Figure 1.1: Magnus force on the rotating cylinder (Sedaghat et al., 2015).

A simple application of Magnus force used in daily life is in sport that utilizing sphere shape balls (Mehta and Pallis, 2001). One of it is football sport, where the player controls the spin on ball so that it curves during the ball travels. Figure 1.2 shows comparison between balls travelled direction. The no spin ball in the centre is not effected by the Magnus force, as wind flow on all side is the similar. Whereas, both spinning balls on the sides are curves due to Magnus force.

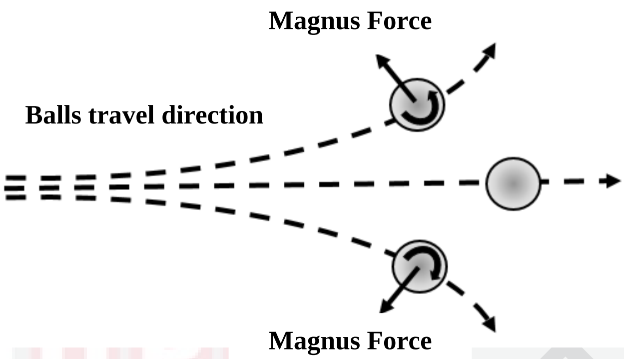

Figure 1.2: Curve ball effected from Magnus Force (Seifert, 2012a).

The significant different of MWT compared to conventional wind turbine is that blades that used to harvest wind energy. Furthermore, to increase the performance of MWT, innovative design of the rotating cylinder was developed. Several researcher used rotating cylinder with fin showed promising results improving lift and torque of MWT (Jinbo, Ceretta Moreira, et al., 2014; Murakami, 2010). Figure 1.3 shows the MWT prototype developed by Japan utilizing spiral fins that coiled around the rotating cylinder blades. Nonetheless, cylinder with spiral fins will increase the complexity of the cylinder blades design.

Figure 1.3: Spiral Magnus wind turbine prototype (MECARO Co. Ltd, 2007).

Moreover, there are several ways to further enhanced Magnus force, for example, by adding plate to the end of cylinder and by adding airfoil fins to the surface of cylinder (Brooks, 1963; Modi et al., 1998; Seifert, 2012a; Takayama and Aoki, 2005; Thom, 1934; Thom and Sengupta, 1932). By using simple innovative approach of sanded surface roughness enhancement. The effect of surface roughness on the rotating cylinder can be demonstrated by the increase in lift coefficient and torque as compared to the smooth surface cylinder (Seifert, 2012b). However, the study on sanded surface roughness enhancement is lacking in boundary layer evaluation (Lopez et al., 2015). Whereas, researchers (Marzabadi, 2012; Marzabadi and Soltani, 2013; Soltani et al., 2011) found that airfoil with sanded surface roughness enhancement reduced its overall performance due to the influence of boundary layer transition, thus causing early turbulence on the airfoil. In addition, researchers (Takayama and Aoki, 2005) shows that boundary layer separation point played an important role in improving rotating cylinder performance as the groove roughness varies on the cylinder surface. Thus, the sanded surface roughness enhancement performance and its effect on the boundary layer is yet to be clearly justified by past researchers.

Nevertheless, there are still lacking in data to support the advantage of surface roughness enhancement (Giudice and La Rosa, 2009; Sedaghat, 2014). Hence, the study in surface roughness is very important in proving significant improvement in MWT performance with different types sanded surface roughness characteristic are achieved. Thus, this study chooses a simple approach in improving Magnus force by using sanded surface roughness on the cylinder surface to avoid in weight and complexity in design. It is vitally important to do experiment research, as there is still gap of knowledge in MWT and enhancement effect of surface roughness. Finally, the study utilized six-component balance and smoke flow visualization to further analysis the effect of sanded surface roughness. In addition, the study will produce a function MWT model that can operate under control environment to fulfil the knowledge gaps. Therefore, this research is hope to shed light on the effect of surface roughness on rotating cylinder and MWT in low wind speed conditions.

In conclusion, six-component balance is used to observe the lift force generated from the vertical-axis single rotating cylinder with different size scales at wind speed 5 m/s. Next, the smoke flow visualization experiment focus on visual analysis to determine the boundary layer separation point on the horizontal-axis single rotating cylinder with selected type of sanded surface roughness enhancement. Finally, the research focus on the improvement torque generated from the MWT model with different type of sanded surface roughness enhancement and the cut-in wind speed. The cut-in wind speed is the lowest wind speed required for the rotor of wind turbine to start rotate.

1.2 Problems Statement

Current state of world technology is going towards renewable and sustainable energy. Wind is one of the green energy that continues to naturally replenish and is sustainable as it is produced from temperature difference due to uneven heating of Earth’s surface by the sun. Unfortunately, Malaysia is one of the countries with low wind speed at an average 2 m/s to 3 m/s, whereas current conventional wind turbine requires optimum wind speed of 11 to 16 m/s to operate efficiently. As of current trend, conventional wind turbine is being developed for countries with high wind speed. Hence, the wind turbine with airfoil shaped blades technology is more developed and matured. Thus, to overcome low wind speed problem, an innovative wind turbine technology was invented by utilizing Magnus effect. This technology is known as Magnus wind turbine that uses rotating cylinder as blades. The rotating cylinder is known to produce more lift force compared to the airfoil shaped blades under similar wind speed condition. However, the main problem of rotating cylinder application is limited information and experimental research on the subject (Sedaghat et al., 2014; Seifert, 2012a). Firstly, the conundrums arising from this lack of information and research would be the scaling effect and the effect of sanded surface roughness enhancement on the Magnus force. Under similar wind speed condition, there is a knowledge gap between rotating cylinder with sanded surface roughness enhancement and smooth surface rotating cylinder with different scale model sizes. This investigation is important to establish whether sanded surface roughness enhancement can improve the Magnus force compared to when using larger cylinder scales. Secondly, there is a gap in the visualization of boundary layer separation point effect on the rotating cylinder with surface roughness enhancement. This observation is critical in order to understand whether the separation point will be earlier or delayed as it will influence the pressure region on the rotating cylinder. Lastly, the application of sanded surface roughness enhancement on the MWT have yet to be explored. Several types of sanded surface roughness are selected to be further investigated for its effect on the torque performance of MWT. This study is important to establish the minimum wind speed required to operate the MWT as the type of sanded surface roughness used varies.

1.3 Research Objectives

The objective of this study is to experimentally investigate the effects of sanded surface roughness on rotating cylinder blades of MWT in low wind speed condition. It comprises of four sub-objectives, which are:

i. To proof the concept of MWT by comparing rotating cylinder with airfoil shaped blades under low wind speed conditions and comparing MWT model with previous past experiment,
ii. To evaluate the performance of vertical-axis single rotating cylinder with varying scale model sizes and the boundary layer effect on the horizontal-axis single rotating cylinder with different type of sanded surface roughness using smoke flow visualization,
iii. To design MWT model, horizontal-axis single rotating cylinder, and vertical-axis single rotating cylinder with different sizes,
iv. To improve the performance of MWT model with different types of surface roughness based on its' velocity ratio, Reynold numbers, tip speed ratio and torque coefficient.

1.4 Scopes of Study

The limitation of the research is the models size. The MWT and scale-up rotating cylinder models are constrained by the wind tunnel test section size with height of 1 m and width of 1 m. The wind speed is limited by the wind tunnel capability. Maximum wind speed for open-loop wind tunnel is 40 m/s and for closed-loop wind tunnel is 50 m/s. The wind speed is measured by anemometer and wind tunnel build-in sensor.

Only one selected sizes of rotating cylinder, cambered airfoil and symmetrical airfoil with similar dimension scaled are used to compare the lift coefficient performance. The Reynolds number range is 12×10^3 to 103×10^3.

The sanded surface roughness with different relative roughness are selected from the market availability of commercial type sandpapers. Eight types sanded surface roughness are selected based of Federation of European Producers of Abrasives (FEPA). The sandpapers standard are P40, P60, P80, P100, P400, P600, P800 and P1000.

The scale-up models size are constrained to test section height as the model attached vertically on six-component balance for measuring Magnus force. The selected wind speed is at 5 m/s to simulate low wind speed condition due to limitation of equipment. Six cylinder size selected based on the aspect ratio of 7.292 due to wind tunnel test section constrain. The size from smaller scaled cylinder gradually increased by 1.23 times, 1.85 times, 2.31 times, 3.19 times and finally 4.23 times. The maximum rotation for motor is 5051 rpm except as the cylinder size increased and the weight further increased. Thus, reduced the capability of the motor to cylinder sizes 3.19 times and 4.23 times to nearly 3052 rpm. The vibration when the cylinder rotating is solved by using support structured that hold the cylinder end, thus stabilizer the rotating cylinder. For rotating cylinder scaled size Reynolds number is 9×10^3 to 38×10^3, whereas for sanded surface roughness enhancement comparison Reynolds number is 9×10^3 to 21×10^3.

The smoke flow visualization is used on selected surface roughness enhancement P800, P100, P80 and smooth surface. The visualization of boundary layer is only focusing on the top side cylinder due separation point between cylinder surface and incoming wind. The Reynolds number range is 197×10^3 to 314×10^3.

Finally, the MWT model research is focusing only on torque performance with different velocity ratio, Reynolds number and tips speed ratio by using different types of sanded surface roughness. The rotating cylinder blades can only rotates up to 1000 rpm. Above 1000 rpm, the blades will vibrate due to only one side of the rotating cylinder blades are being hold by the hub. Power usage to rotate the cylinder blades is below 30 W. However, the study is only focusing on the improvement of sanded surface roughness enhancement toward torque performance. The Reynolds number range is 54×10^3 to 108×10^3.

1.5 Outlines of the Thesis

The thesis outlines have five chapters. The chapters are categorize as following, Chapter 1 Introduction, Chapter 2 Literature Review, Chapter 3 Methodology, Chapter

4 Results and Discussions, and finally, Chapter 5 Conclusions and Recommendations. The details of chapters contain are described as below.

Chapter 1 briefly introduced the backgrounds of study focus, motivation, problem statement, objective to achieve in this study, and finally scopes of study.

Chapter 2 is review on all the information and knowledge regarding to the study focus to fully explored and deepen the understanding in the applications of MWT, the field of Magnus forces, and surface roughness effect. Moreover, theory for single rotating cylinder and MWT are also included in this chapter.

Chapter 3 is methodology approach used to achieve the experiment and its touch regarding procedures and apparatus used in the study in order to accomplish the target objective and results. Design, fabrication, and assembly of MWT model and single rotating cylinder are discussed.

Chapter 4 presented the results attained during experimental study and discussed to help in understanding the study objectives. The study results are related to past research findings for further understanding.

Chapter 5 is the summary of the study, the findings conclusions, contribution of the study, and finally, the recommendation for future study are suggested.

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